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FOURTH US ARMY WORKSHOP ON LOW HEAT REJECTION ENGINES

29–31 March 1989

Summary of Main Presentations
Programme

DAJA 45-89-M-0043

INDUSTRIAL UNIT OF TRIBOLOGY
The University of Leeds

FOURTH US ARMY WORKSHOP ON

LOW ι ˜AT REJECTION ENGINES

at

Bodington Hall, University of Leeds, England

29-31 March 1989

PROGRAMME

Wednesday 29th March

Assemble at Bodington Hall where the Reception Desk will be open from 4 pm.

7:00 pm	Reception and Dinner	

Thursday 30th March

9:00 am	Welcome	Dr C N March Industrial Unit of Tribology
9:10 am	Opening Remarks	Dr R E Reichenbach US Army European Research Office
9:30 am	Overview - GENERAL CONCEPTS OF LOW HEAT REJECTION ENGINES	Professor F Wallace, University of Bath
9:50 am	Session I	
	MATERIALS FOR INSULATED ENGINE COMPONENTS - CHARACTERISTICS AND TECHNOLOGY	
	Session Chairman	Professor D Dowson, University of Leeds
	Principal Speaker	Dr R Wordsworth - T & N Technology
	Individual Contributions	
10:45 am	Coffee	
11:00 am	Discussion and Summary	
1:00 pm	Lunch	
2:00 pm	Session II	
	MECHANISMS OF WEAR OF CERAMIC MATERIALS	
	Session Chairman	Dr R Stevens - University of Leeds
	Principal Speaker	Professor D Dowson, University of Leeds
	Individual Contributions	
3:00 pm	Tea	

Thursday 30th March

3:15 pm Discussion and Summary

5:15 pm Session Closes

7:00 pm Coach leaves for Workshop Dinner at Chevin Lodge Hotel, Otley, subsequently returning to Bodington Hall.

Friday 31st March

9:00 am Session III

SURFACE-LUBRICANT INTERACTIONS AND FRICTION

Session Chairman Dr C M Taylor, University of Leeds

Principal Speaker Dr A R Lansdown, Swansea Tribology Centre

Individual Contributions

10:15 Coffee

10:30 am Discussion and Summary

12:30 pm Concluding Remarks Dr R E Reichenbach
US Army European Research Office

1:00 pm Lunch

2:00 pm Delegates Depart

Optional tour of Leeds Tribology Laboratories available.

Workshop Organiser : Dr C N March
Industrial Unit of Tribology
University of Leeds
Woodhouse Lane
Leeds LS2 9JT

Tel: (0532) 332160

OVERVIEW

GENERAL CONCEPTS OF LOW HEAT REJECTION ENGINES

Professor F.J. Wallace

CERAMIC COATINGS AND MONOLITHS IN ENGINES - A BROAD ASSESSMENT OF FUTURE POTENTIAL

by F.J. Wallace, W. Alexander and H. Reiter

ABSTRACT

The paper describes the basic principles underlying the operation of low heat loss engines, and the magnitude of the efficiency improvements which are theoretically achievable.

The effect of varying degrees of thermal insulation on various operating parameters is examined in some detail, as is the relationship between degree of insulation and ceramic coating thickness. The effect on ceramic materials of severe surface temperature oscillations and the resultant thermal stress gradients is also discussed.

In the following section, the paper describes methods of construction adopted both for ceramic inserts and coatings, and rig tests for the assessment of thermal fatigue under both load and firing cycling.

The paper does not attempt to draw any general conclusions.

1. INTRODUCTION

Low Heat Rejection (LHR) Engines have been the subject of intensive research over the last 10-15 years, (refs. 1-11). The original impetus for this work was provided by the recognition that the already highly efficient automotive Diesel engine (η_{brake} = 38-40%) could be improved only by a major change in its mode of operation. This is illustrated by the simple heat balance of fig. 1a which indicates that, with fuel energy input at 100%, the major 'losses' are 32% to exhaust and 30% to coolant.

The Second Law of Thermodynamics requires that any heat engine converting a heat input into work must reject part of that heat input; an ideal heat engine operating on the 'Carnot' cycle achieves a max. efficiency, in terms of source temperature T_{source} (approx. 2100K) and sink temperature T_{sink} (approx. 300K) given by

$$\eta_{CARNOT} = \left[1 - \frac{T_{sink}}{T_{source}}\right]100 = \left[1 - \frac{300}{2100}\right]100 = 85.7\%$$

i.e. it only rejects 14.3% of the heat received. In practice such high values of efficiency and low values of heat rejection cannot be realised for a number of reasons including

a) the inability of constructional materials to withstand temperatures of the order of 2000K.

b) the inherent thermodynamic irreversibility of the combustion process.

c) the impossibility of expanding the products of combustion sufficiently to reach temperatures approaching the theoretical sink temperature, i.e. the temperature of the surroundings.

d) the need for lubrication ruling out high surface temperatures.

While metals (cast iron, steel and aluminium) were the only available materials of construction water or air cooling had to be used to maintain temperatures at permissible levels, typically > 350 C for Al; > 450 C for C.I. or steel. The resultant heat loss to coolant, as shown in fig. 1a, is typically of the order of 30%. Obviously a significant reduction in this rejected heat fraction could be expected to lead to improvements in efficiency. The method of achieving such improvements is to find materials of construction capable of operating at the resultant higher temperature levels, of which ceramics are the outstanding example.

Any attempt to reduce the second major component of heat rejection, i.e. the exhaust loss, is limited by fundamental 2nd Law considerations.

Fig. 1b shows a somewhat optimistic assessment of the redistribution of energy in an engine with approx. 43% suppression of the normal heat loss to coolant, achieved by the application of a notional PSZ thermal barrier coating of 2-3 mm thickness (k = 1 W/mK). It can be seen that the exhaust heat loss has actually increased from 32% to 37%, while the useful work output has increased from 38% to 46%, the latter figure being somewhat optimistic.

The reasons for the fact that only a small proportion of the suppressed heat loss reappears as a gain in useful work will be discussed later. Even so, the implication of 40 to 45% suppression of heat loss is an increase in mean combustion chamber wall temperature from between 250 and 300 C to between 600 and 800 C, with all the attendant problems of materials, lubrication etc.

There remains the possibility of recovering, in addition to the gain in cylinder work, at least part of the additional exhaust energy loss by the use of an expansion turbine and, at least in theory, the use of a so-called bottoming cycle.

These will again be discussed in the next section.

2. THERMODYNAMIC ASPECTS

2.1 Basic engine types [Figs. 2a,b,c,d]

For the purpose of analysing the effect of thermal insulation on engine performance and operating conditions, it is appropriate to divide engines into 4 broad categories. (It is assumed that only Diesel engines are being considered).

a) **Naturally aspirated engines** [fig. 2a]

These draw air directly from atmosphere and reject exhaust to atmosphere. This type is used mainly for small stationary or marine units and is very limited in its output potential.

b) **Turbocharged engines** [fig. 2b]

The turbocharger is a simple back-to-back arrangement of exhaust driven turbine - usually of the radial inflow type, and supercharging compressor - usually of the centrifugal type.

Turbochargers are mechanically separate from the engine and operate under their own equilibrium conditions. By supplying the engine with pre-compressed, i.e. denser, air the power output can be raised approximately in proportion to the increase in density relative to ambient, up to levels of the order of 3 times the corresponding naturally aspirated condition.

The turbocharger thus makes use of the exhaust gas available energy which would otherwise be wasted.

c) **Compound engines** [fig. 2c]

If the exhaust gas available energy rises above a certain level, as it does in thermally insulated engines, a surplus may be created above the requirements of the turbocharger. Under these conditions mechanical arrangements can be devised to use at least part of the additional energy.

Such means include

either

the use of a second turbine mechanically linked to the engine system

or

a geared turbochager in which energy surplus to the requirements of the compressor is again fed to the engine system.

Since compound engines thus deliver increased output without additional fuel, their thermal efficiency should also be higher.

d) Compound Engines with bottoming cycles [fig. 2d]

The gases finally leaving the turbine of a compound engine, having expanded to atmospheric pressure, still have some available energy arising from excess temperature above ambient. This energy can be partly utilised in a so-called bottoming cycle, with the still hot exhaust gas providing a heat source for a low boiling point vapour cycle. However, such systems are cumbersome, costly and bulky, and have not been employed in practice.

2.2 Effect of degree of insulation on operating temperatures and other conditions

The effect of degree of insulation on various operating parameters is shown in figs. 3a to 3f for a turbocharged 6 cylinder direct injection Diesel engine having a rated output of 200 kW at 2600 rpm.

Fig. 3a liner top temperature

This is seen to rise steeply with degree of insulation, rising from approx. 450K (177 C) to 950K (677 C) with 60% reduction in heat transfer. Although liner temperature falls away rapidly with increasing distance from TDC, severe lubrication difficulties would arise, even with special oils.

Fig. 3b mean piston crown temperature

This increases even more steeply than liner temperature, rising to a max. value of approximately 1170K (897 C). Such temperatures can be accommodated only by special alloy materials (e.g. Nimonic) or ceramics, in either coating or monolith form. In the case of alloy materials with relatively high thermal conductivities (typically k = 50 W/mK) it is essential to use air gap designs, while with very low conductivity ceramics (e.g. PSZ or glass ceramics with k values between 0.5 to 2.5 W/mK) the material can be used directly.

Fig. 3c Exhaust gas (i.e. turbocharger turbine inlet) temperatures
This is seen to depend critically not only on degree of insulation but also on engine speed with the latter effect being particularly pronounced for the standard, i.e. normally cooled, engine. At 2600 rpm, exhaust temperature rises from 900K (627 C) to 1010K (737 C). This relatively modest rise does not imply resort to new materials, in fact petrol engine exhaust temperatures reach values as high as 900 C and use conventional turbocharger materials.

Fig. 3d Available exhaust energy
Since air mass flow depends directly on engine speed, and since exhaust energy is a function of mass flow, of exhaust gas temperature and of the available exhaust pressure ratio, all of which increase with engine speed, one may expect a steeply rising trend of exhaust energy with engine speed. The increase with degree of insulation is comparatively modest in view of the quite small increase in exhaust gas temperature (fig. 3c), being approx. 12 kW from 48 kW, at 2600 rpm, i.e. 25%. At the lowest speed of 1000 rpm there is virtually no gain.

Fig. 3e Inlet manifold (i.e. boost) pressure
In a turbocharged engine this directly reflects the level of available exhaust energy, and hence rises both with engine speed and with increase in exhaust gas temperature.

Fig. 3f Volumetric efficiency (reduction of charge density)
A distinctly adverse effect of hot combustion chamber walls is the heating effect on the entering air during the suction stroke. This reduces the density of the final trapped charge and hence the amount of fuel which can be burned. In naturally aspirated engines (fig. 2a) this is disastrous; in turbocharged engines the higher boost pressures achieved by partially insulated engines (fig. 3e) at least partly compensate for the temperature effect on density. Fig. 3f shows that the reduction of volumetric efficiency is particularly serious at low engine speeds when the time available for heat transfer is greatest.

2.3 Relationship between coating thickness and degree of insulation [Fig.4]
Fig. 4 shows the effect of coating thickness on the energy balance of turbocharged two- and four stroke engines. The material is PSZ with an assumed thermal conductivity k = 2 W/mK. In addition to the effect of coating thickness, these diagrams also show two limiting cases A and B, the former for a hypothetical insulator of zero conductivity giving truly adiabatic conditions, and the latter for a sufficiently thick layer of a 'real' insulator to give zero nett heat loss over a complete cycle, but still allowing heat flow into and out of, the material, i.e. a thermal storage effect.

The benefits of insulation in terms of indicated piston work are seen to be greater for 2 stroke than for 4 stroke engines. Percentage coolant heat loss decreases asymptolically with coating thickness, 3 mm giving rather less than 50% reduction. However, thermal conductivity has a pronounced effect, and with quoted k values for certain materials and coating structures below 1 W/mK better results can be achieved.

It is interesting that even the limiting case B only leads to a 3.2% improvement in piston work for the 4 stroke engine.

2.4 Surface temperature effects [Figs. 5a and 5b]
The violent gas temperature fluctuations in engine cylinders, typically from 400 K to 2100 K, lead to marked surface temperature savings on coating surfaces, typically of the order of ± 150 C round mean temperatures of approx. 1000K (727 C), depending on coating thickness and thermal properties (k,ρ,c).

These surface temperature fluctuations are rapidly attenuated within the material (fig. 5b), with amplitudes decreasing by 80% within approx. 0.12mm from the surface. It is obvious that the resultant steep and rapidly oscillating temperature gradients set up severe thermal stresses, alternating between compressive and tensile. These, in turn, can lead to severe surface damage, if coatings are insufficiently compliant, and if residual stresses resulting from the deposition process itself are already present.

In addition, load cycling over varying periods, from idling to full speed and load, imposes further severe stresses, with both mean surface temperatures and the associated temperature swings varying continuously.

In our own work at Bath we have devised rig tests on fully instrumented ceramic discs to simulate both load cycling and the high frequency cycle associated with engine speed.

4. PROBLEMS OF PRACTICAL IMPLEMENTATION

4.1 Methods of construction

The pioneering work of the Cummins Engine Co. in the late 70's, associated with the name of Kamo, (1), gave a great impetus to the application of ceramics in engines. Certain design 'rules' eventually emerged, based on interference fitted PSZ inserts for pistons, liners and cylinder heads, married to C.I components (fig. 6). This choice was based on a combination of thermal, mechanical and chemical properties as well as simplicity of construction.

Thermal properties include low conductivity (k = 2-4 W/mK) thermal expansivity ($\alpha = 10 \times 10^{-6}$) compatible with C.I and low specific heat (0.42kJ/kg K).

Mechanical properties include relatively high Young's modulus (E = 210 GPa), high bend strength (= 600 MPa), but unfortunately also high density (ρ = 5-6 $\times 10^3$ kg/m^3). Chemical properties include high resistance to corrosion and erosion.

Engines using PSZ inserts have run on an experimental basis, with some indication of marginally improved performance, but have suffered from very limited life.

The superficially simpler coating route has been followed by many workers. Until recently PSZ has been the favoured material, but it has proved very difficult to produce durable coatings more than 1 mm thick, the main problems being spalling and cracking.

More recently much work has been done on ceramic inserts for prechambers in IDI engines where the retention problem is eased somewhat by the physical configuration (fig. 7). Current work on prechambers at Bath includes a wide range of materials, including Syalon, RBSN, PSZ and aluminium titanate (see table 1 for properties).

Still more recent work at Bath has considered glass ceramics as a possible material for piston caps in view of their low conductivity (k = 1.5-2 W/mK), low expansivity and relatively high strength (E = 150 GPa).

Retention methods present considerable problems, but design solutions at least for IDI, flat topped pistons, are beginning to emerge (fig. 8).

4.2 Thermal fatigue for load and firing cycles

Reference has been made, in section 2.4, to the large thermal stresses arising from temperature fluctuations within a relatively thin surface layer of the ceramic material. At Bath we have devised rigs for continuously monitoring the behaviour of disc shaped monolithic or coated speciments under both types of thermal loading conditions.

a) **Thermal shock rig** [fig. 9]

This is intended to expose the specimen to *alternate high intensity* heating ($q = 500\ kW/m^2$) and rapid cooling under closely controlled conditions. Heating and cooling times, as well as heating intensity can be separately adjusted. The specimen is fitted with surface thermocouples both on the front and the back face and structural changes within the material are continuously monitored using an acoustic emission probe.

Work to date has been limited to glass ceramic discs, but will be extended in the near future to PSZ coated discs with varying coating thicknesses from 0.5 to 2.5 mm on C.I or aluminium substrates. The latter tests will also provide valuable ionformation on bond coat durability.

b) **Engine simulation rig** [fig. 10]

This is based on the single cylinder Petter PH 1WQ engine which was used for earlier work on all metallic pistons with air gap insulation. The deep bowl piston has been replaced by a flat topped version, and the normal inlet and exhaust valves have been replaced by a single inclined valve alternatively admitting and rejecting externally circulating hot air. The combination of hot air and high compression ratio resulting from the design of the rig lead to temperature and pressure fluctuations approaching those of the firing engine.

The test specimen, again equipped with surface thermocouples, is retained in the head by a split ring clamp (fig. 11).

Again both solid ceramic and coated specimens will be tested, under continuously monitored conditions.

5. CONCLUSIONS

The application of ceramics to engines, in spite of a substantial research effort in the U.S.A., Japan and Europe, is still very much in its infancy.

The problems of mechanical integrity and acceptable reliability in service are formidable, and as yet no coherent design philosophy has emerged.

The potential gains in thermal efficiency are relatively modest, and require a considerable degree of system sophistication for their realization.

On balance it seems probably that low heat loss engines using ceramic components will enter service first in the military, rather than the civilian field, but the technology is now developing rapidly and we may well see significant numbers of 'ceramic' engines before the end of the century.

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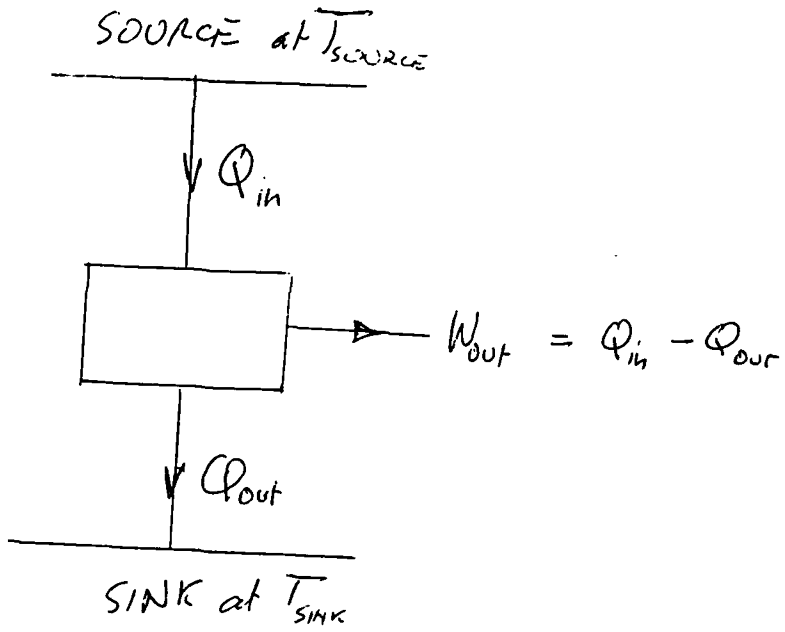
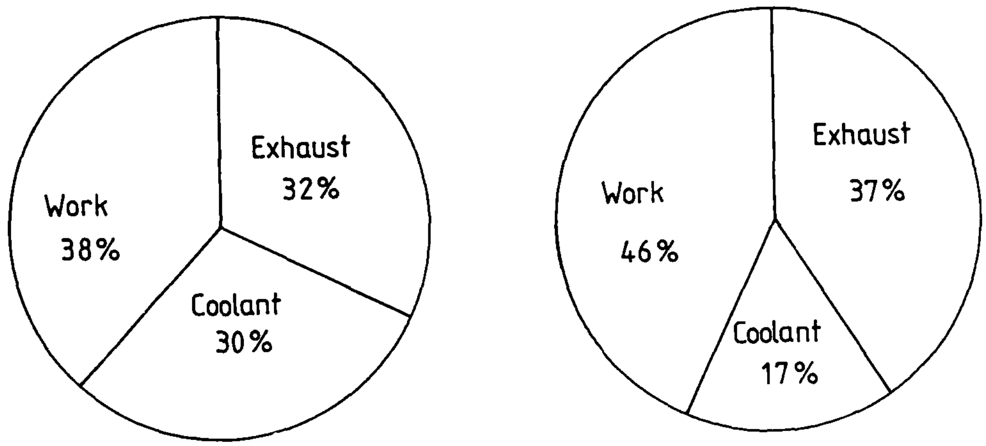


CARNOT ENGINE

$$\eta_{CARNOT} = \left[1 - \frac{T_{SINK}}{T_{SOURCE}}\right]100$$

$$= \left[1 - \frac{300}{2100}\right]100$$

$$= 85.7\%$$



(a) Standard Engine (b) Insulated Engine

FIG. 1 Energy Balance Comparison

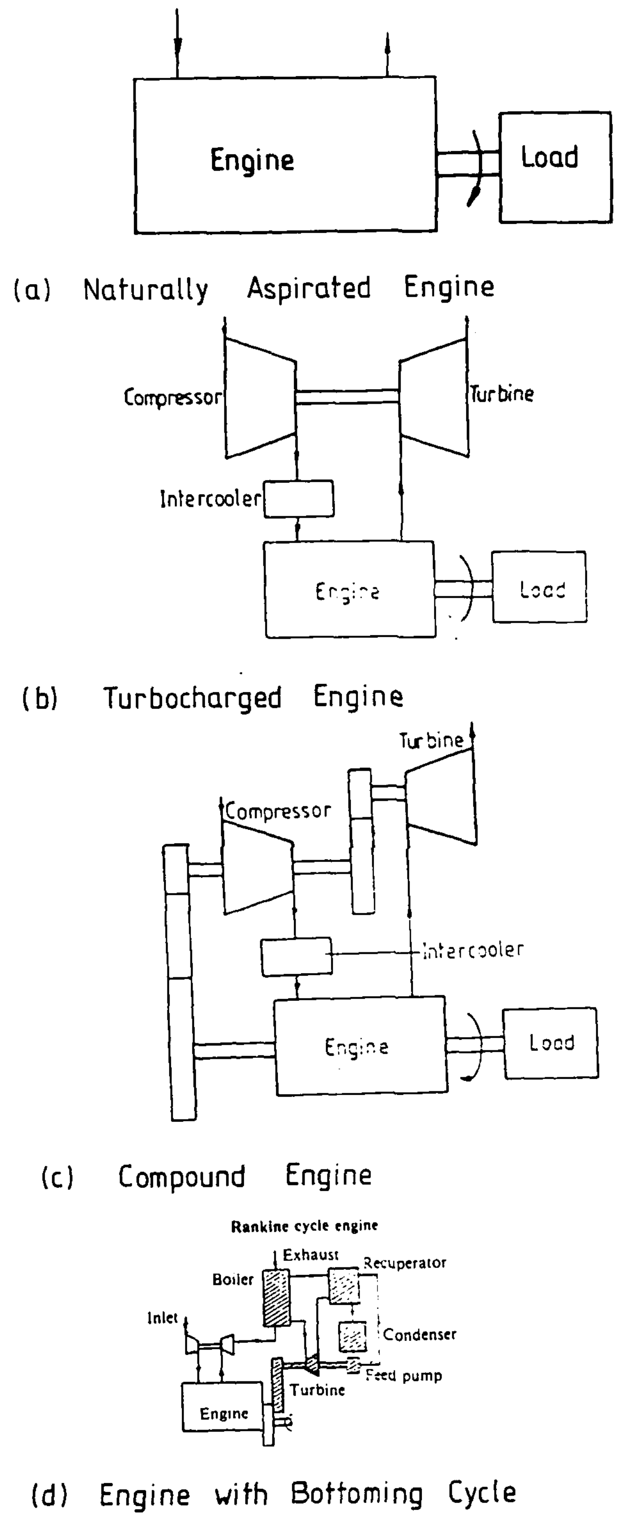


FIG. 2 Basic Engine Types

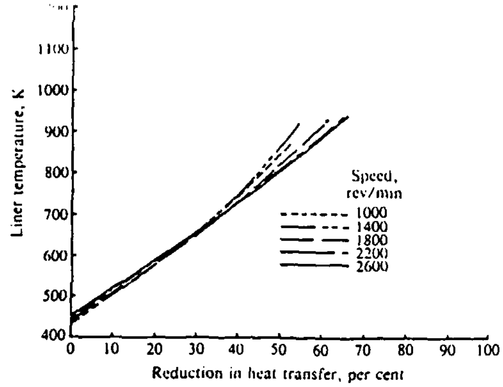


Fig. 3a The variation of liner top temperature with degree of insulation

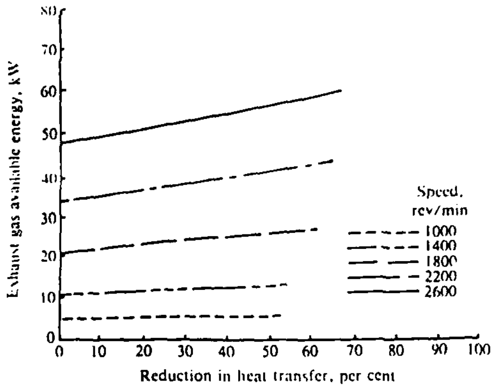


Fig. 3d The variation of turbine available energy with degree of insulation

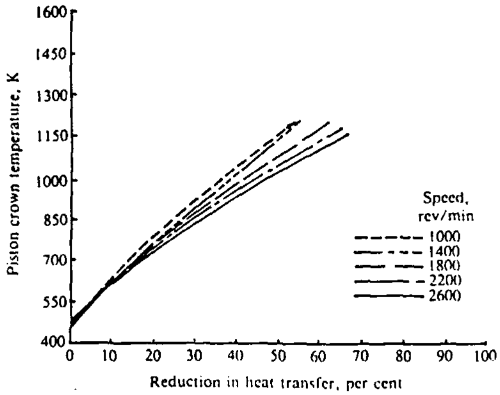


Fig. 3b The variation of mean piston crown temperature with degree of insulation

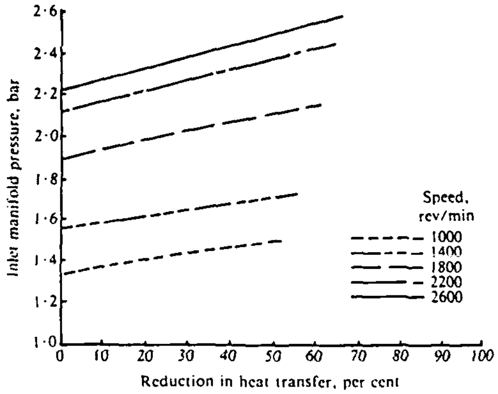


Fig. 3e The variation of turbocharger boost pressure with degree of insulation

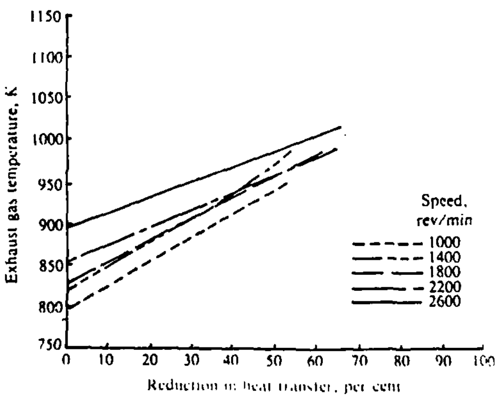


Fig. 3c The variation of mean turbine inlet temperature with degree of insulation

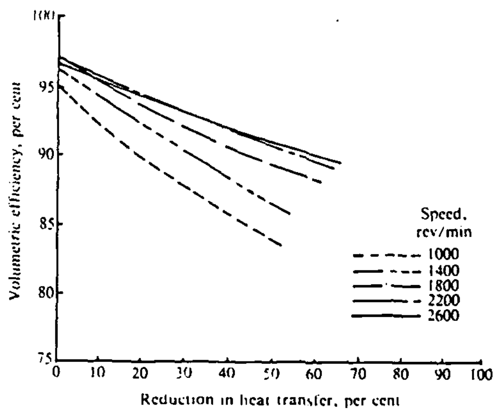


Fig 3f Deterioration in volumetric efficiency (based on inlet manifold conditions) with degree of insulation

FIG. 3 Effect of Degree of Insulation

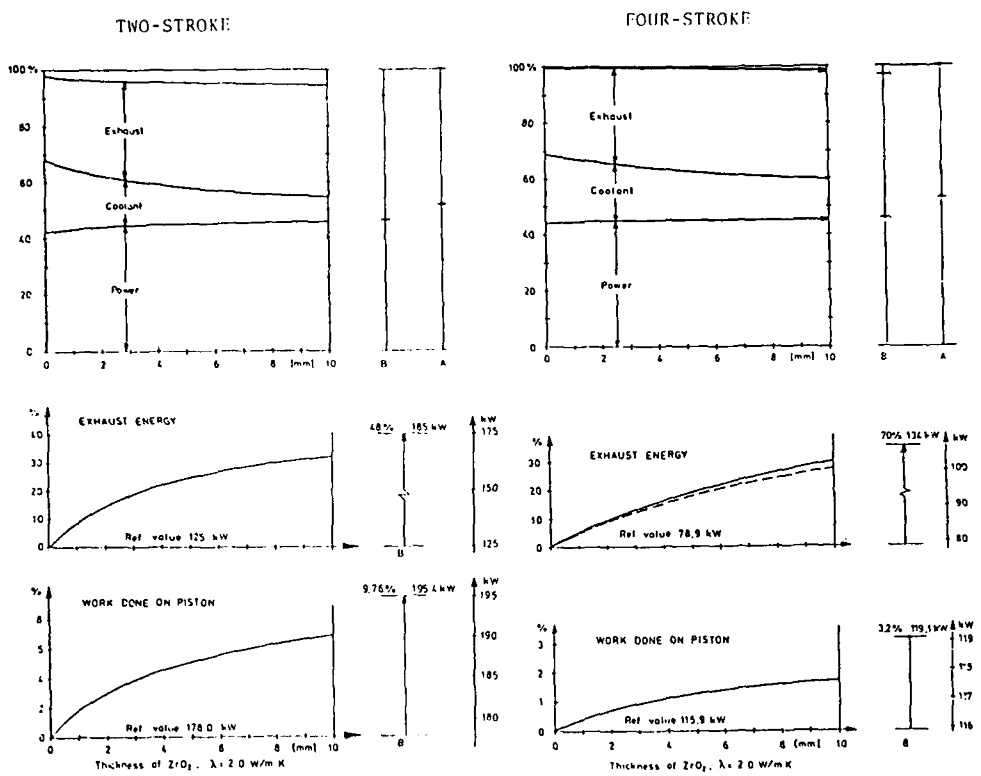


FIG. 4 Change of the engine energy balance due to the thermal barrier.

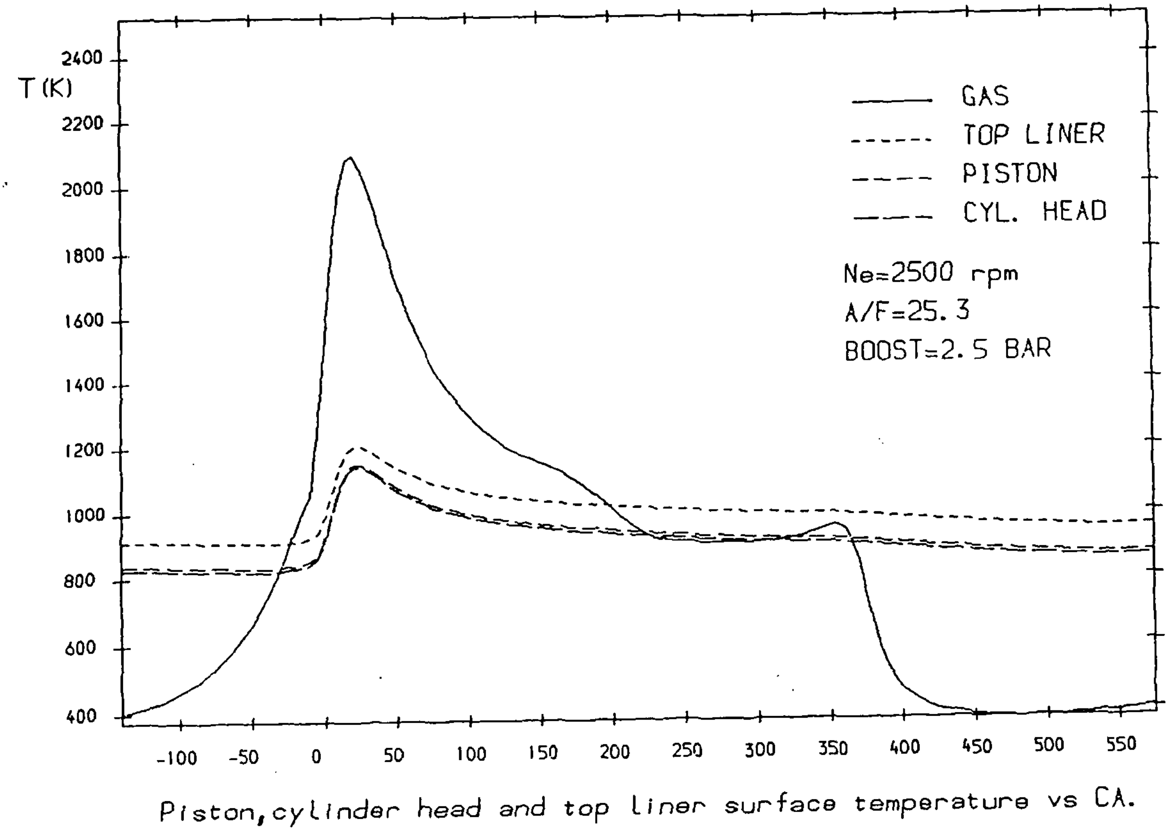
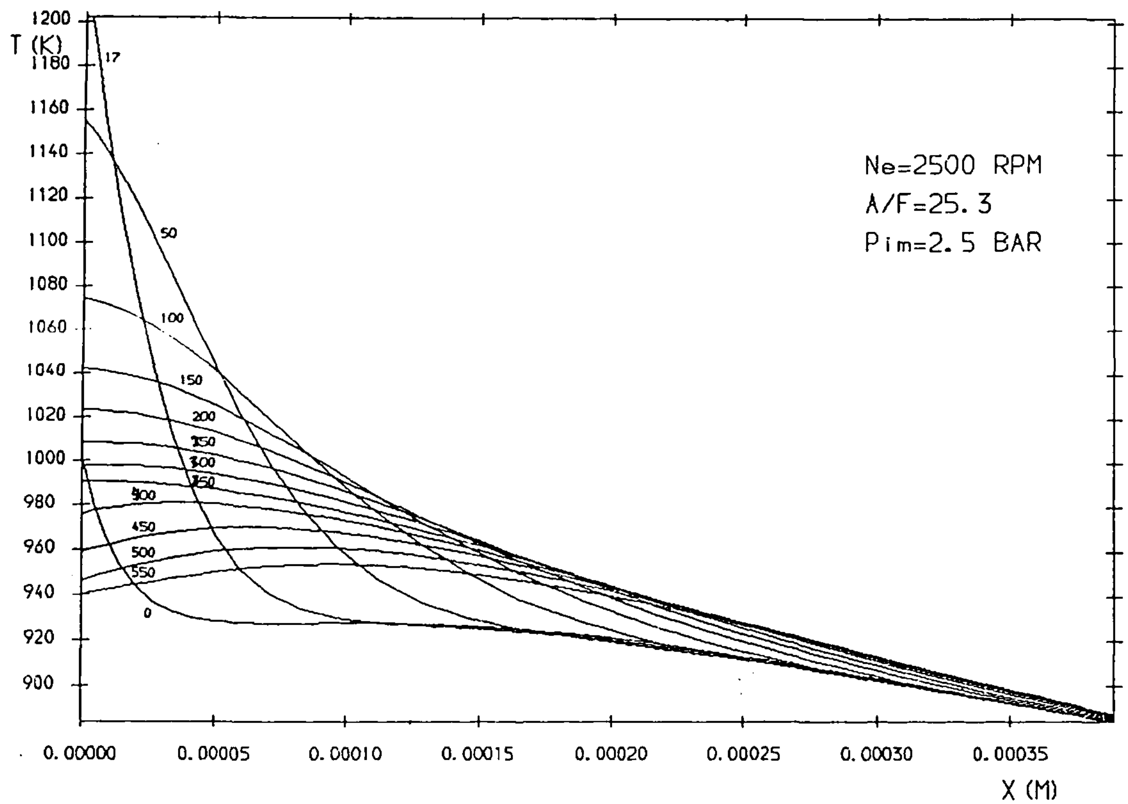


FIG 5a Insulated Engine (1·5mm Zirconia)



Temperature wave through the zirconia material at different CA posit

FIG. 5b Insulated Engine

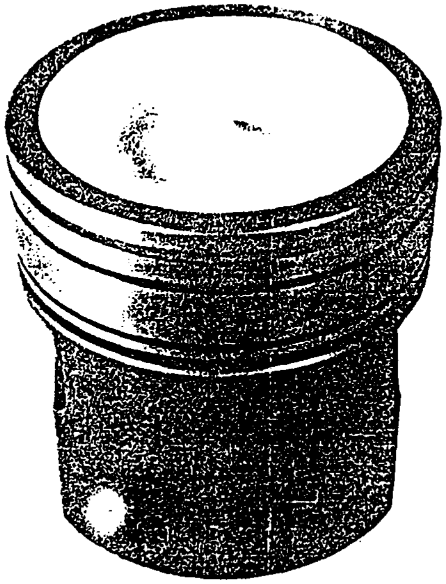


Fig. 6a - Insulating piston assembly

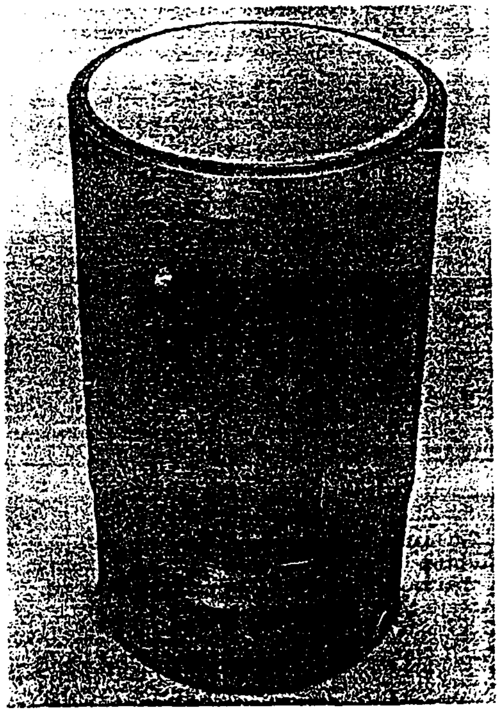


Fig. 6b - Insulating cylinder liner assembly

FIG.6 PSZ Inserts

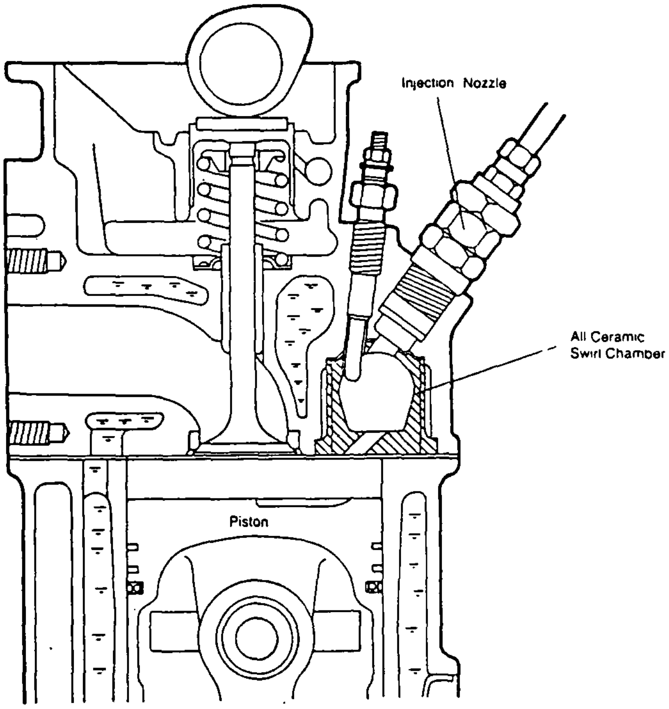


FIG. 7 Ceramic Prechamber

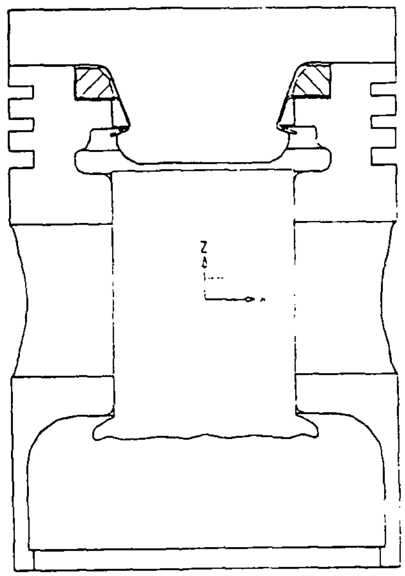


FIG. 8 Piston with Glass Ceramic Cap

Overall Schematic of Thermal Shock and Thermal Conductivity Rig

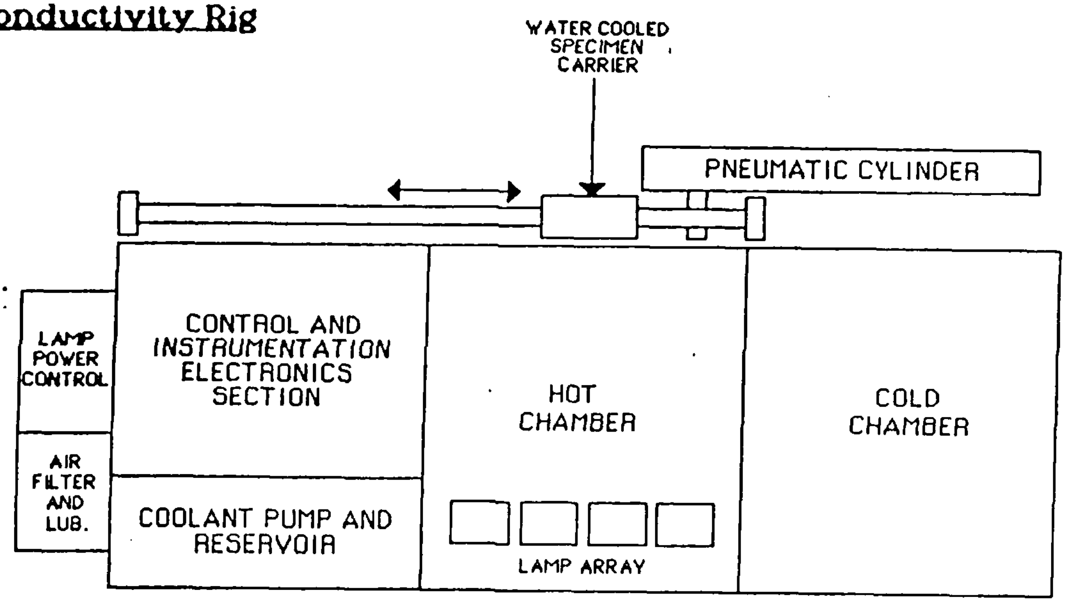
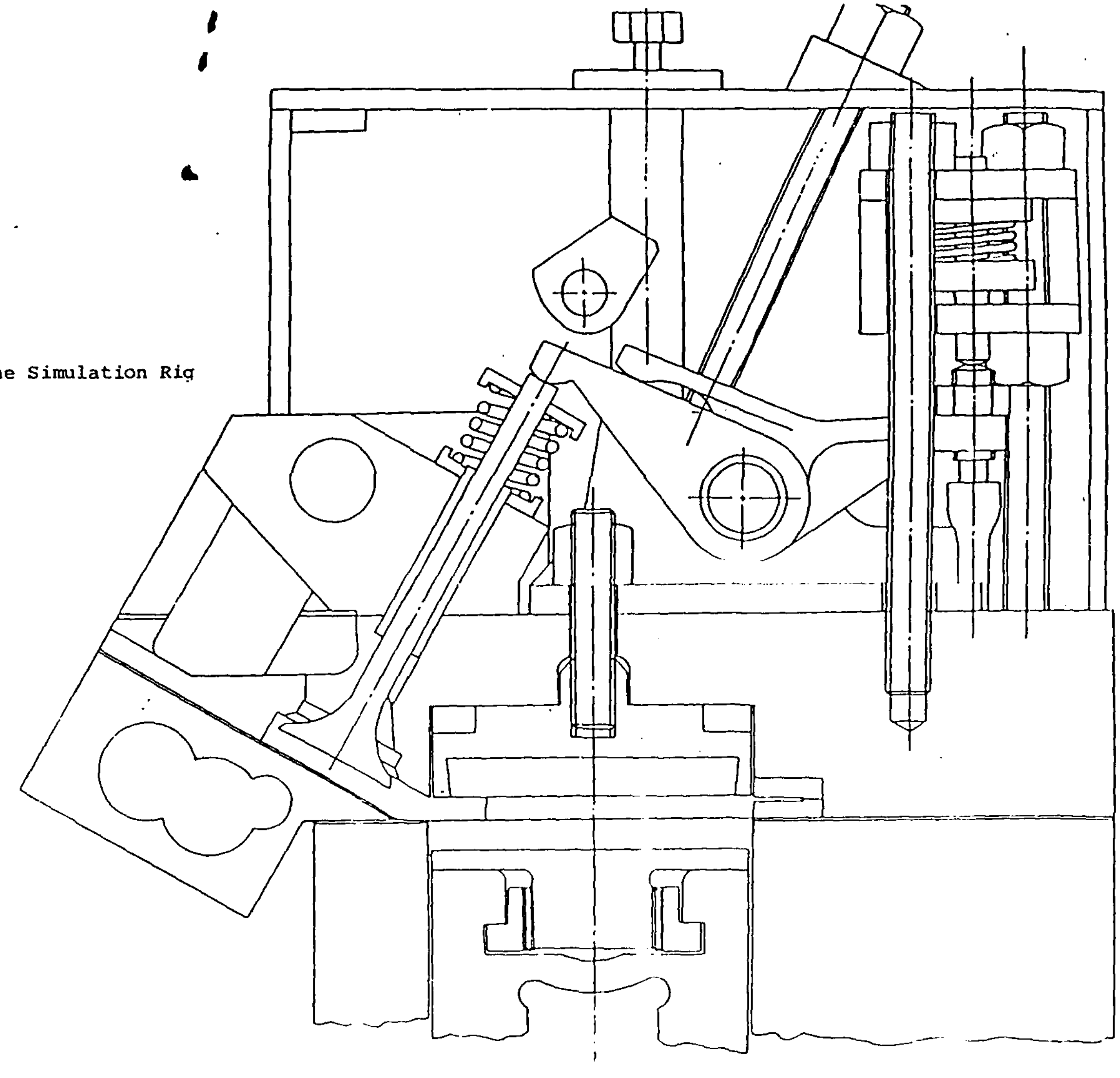


FIG. 9

FIG.10



Cylinder Head Engine Simulation Rig

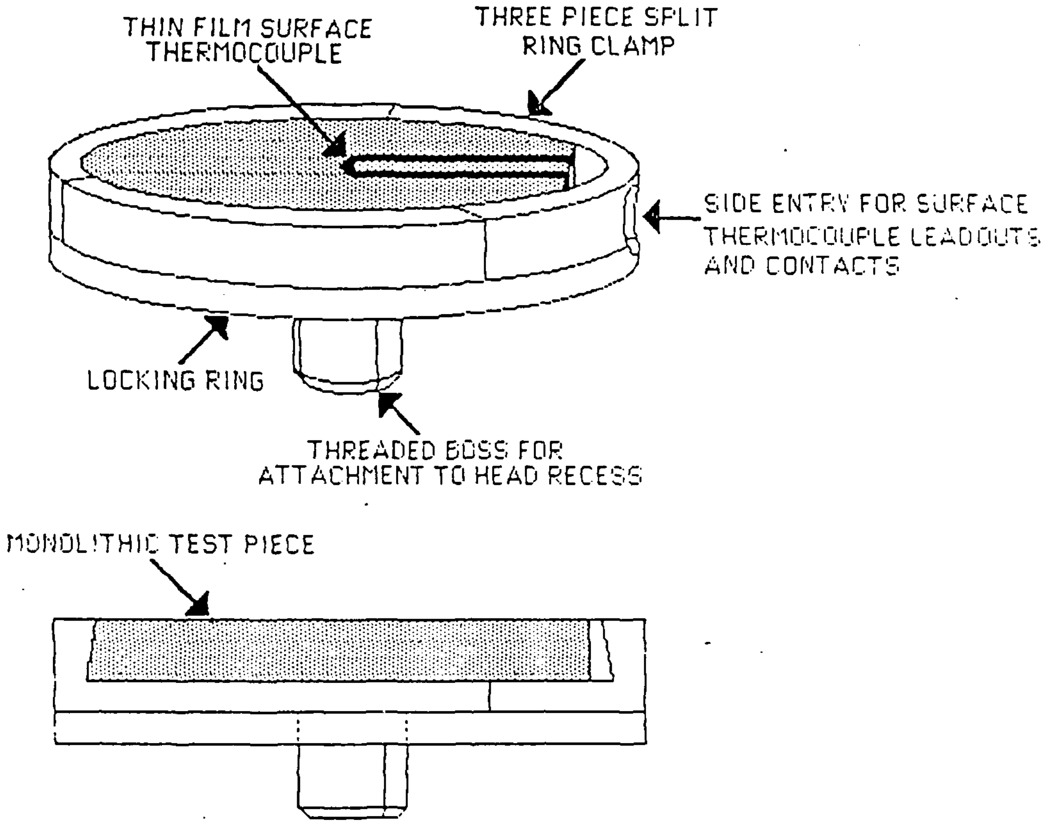


FIG.11 Ceramic Disc Retention

SESSION I

Summary of Main Presentation

MATERIALS FOR INSULATION ENGINE COMPONENTS
CHARACTERISTICS AND TECHNOLOGY

Dr R. Wordsworth

APPLICATION OF CERAMIC MATERIALS IN RECIPROCATING ENGINES

by

R.A. WORDSWORTH

CERAMICS LABORATORY
T & N TECHNOLOGY LTD
RUGBY

On current designs of internal combustion engine it is essential to provide a system for cooling those components situated either within or close to the combustion chamber. This is usually achieved by pumping water or air through a labyrinth of passageways to maintain components or their lubricants at temperatures where they are physically and chemically stable. However, the provision of a cooling system on an engine reduces the efficiency because heat is dissipated to the surroundings and also because ancilliary components such as pumps consume energy. It is with a view to reducing the cooling requirements of reciprocating engines that considerable effort is now being directed towards the use of ceramic materials, both as coatings and monolithic pieces for engine components.

Ceramics offer a wide range of material properties which are generally superior to those of metals, namely, chemical resistance, wear resistance, hardness and low density. Some of these materials have tensile strengths comparable with those of steels, but unlike the latter, many ceramics can maintain their strength at temperatures in excess of 1000 C. Noble though these properties are, it is difficult to exploit them fully in engines for two reasons :

(i) the fracture toughness of ceramics is low, and failure occurs by rapid brittle fracture, following a period of slow crack growth. Typical iniiation sites for cracks are small material defects such as inclusions or porosity, and surface features such as deep grinding marks. It is commonly believed that material flaws as small as 25-50 microns diameter could lead to failure in highly stressed engine components.

(ii) fracture strength can only be expressed meaningfully in terms of a probability distribution, and this is dependent upon the previous loading history. Failure of ceramic components is therefore difficult to predict and is frequently catastrophic.

Clearly, reliability of materials is of paramount importance for engine applications. Improvements in ceramic component reliability can be achieved in several ways including :

(i) careful selection of candidate material

(ii) Providing a greater margin between fracture stress and working stress by giving considerable attention to component design.

(iii) stringent process control to ensure repeatability of materials quality

(iv) large scale proof testing of components under conditions which closely represent those found in service

(v) non-destructive evaluation (NDE) of material quality at each stage of the process route

It is towards the first two of these considerations, i.e. material selection and component design that attention is directed in this presentation.

The choice of the most appropriate ceramic material is often difficult, requiring a thorough understanding of both the proposed operating environment and how the available material properties will contribute to component performance. Frequently enhancements in some material properties can only be realised with the compromise of others, e.g. hardness vs toughness and it is therefore necessary to know which features are the most important in each situation.

Good design methodology is essential if the maximum potential is to be exploited from the available material properties. This requires a sound knowledge of component manufacturing technology and techniques for joining ceramics and other materials.

The respective roles played by material properties and component design are illustrated in a review of engine components in which ceramic materials have been employed.

SESSION II

Summary of Main Presentation

MECHANISMS OF WEAR OF CERAMIC MATERIALS

Professor D. Dowson

MECHANISMS OF WEAR OF CERAMIC MATERIALS

by

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INTRODUCTION

The use of hard bearing materials to resist wear dates back to antiquity. Examples include stone pivot bearings in Sumaria (c. 2500 B C) and the fine stone-studded (c 16th century A D) oak axle from a cart found at Torp in Denmark in 1877. It is quite likely that early ceramics were used to support wooden spindles and to act as bearings in simple tools used in various crafts.

The development of plain bearing technology in the 19th and 20th century led to the use of iron or steel shafts and relatively soft bearing materials. There was little need for ceramic materials in tribology at this stage. but in due course two properties of ceramics made them increasingly attractive as bearing materials. One was their inertness (e.g. for medical engineering applications) and the other was their ability to operate at high temperatures (e.g. in ovens. and engines). Tungsten carbide also established itself as a cutting tool material.

In this talk some of the basic features the tribological characteristics of ceramics will be outlined and comparisons will be made with more conventional pairs of sliding materials.

WEAR TESTS

Studies of the wear characteristics of ceramics are usually carried out on pin-on-disc or pin-on-plate machines. These permit well controlled conditions to be maintained. while permitting ranges of loads and speeds to be applied under well controlled environmental conditions (wet, dry, temperature).

Wear Factors

For ductile materials it is generally found that the volume of material removed by wear (V) is proportional to the applied load (P) and the sliding distance (X). Hence,

$$V \propto PX \tag{1}$$

or

$$V = k\,PX \tag{2}$$

- where (k) is a wear factor representative of the combination of materials and the test conditions. The units of (k) are conveniently recorded as (mm^3/Nm).

Ceramics often exhibit an increase in (k) as either the load or the sliding distance increase, but it is nevertheless useful to compare the wear factors obtained from equation (2) for different combinations of ceramic and non-ceramic materials to indicate their relative resistance to wear under comparable conditions.

Some care has to be exercised in making such comparisons, but the following 'approximate' values indicate the orders of magnitude of (k) for various combinations of materials.

Material Combination	Wear Factor (k) mm^3/Nm
Steel on Steel	10^{-5}
Steel on Alumina	10^{-5}
Hot Pressed Silicon Carbide on Hot Pressed Silicon Carbide	10^{-5}
Silicon Nitride on Silicon Nitride	10^{-6} - 10^{-5}
Alumina on Steel	10^{-7}
Sialon on Sialon	10^{-7}
Sintered Silicon Carbide on Sintered Silicon Carbide	10^{-7}
Polyethylene on Alumina [wet]	10^{-7}
Tungsten Carbide/Cobalt- on Tungsten Carbide/Cobalt	10^{-8}
Polyethylene on Alumina [dry]	10^{-8}
Alumina on Alumina	10^{-8} - 10^{-9}
Polyethylene on Sapphire	10^{-9}

VAMAS Tests

The Versailles project on advanced materials and standards (VAMAS) has involved the evalutation of steel and alumina materials on modified pin-on-disc machines in which test balls were loaded against various discs in different laboratories. A similar study was undertaken by the UK Wear Test Methods Working Group using a single pin on a rotating disc. A typical set of results from the participating laboratories (steel pins and discs) will be shown.

WEAR MECHANISMS

At modest loads and speeds many ceramics appear to wear by the familiar mechanisms of flow and deformation. Fine debris, often in the form of thin platelets is observed. At higher loads brittle fracture of the surface leads to enhanced wear and larger wear debris is readily detected.

SUMMARY

Experimental information on the wear of ceramics indicates that they offer remarkable resistance to wear. They are, however, subjected to increasing wear as the load, speed or sliding distance increase. The wear debris is generally highly abrasive and the separation of this debris from other tribological components in machinery may be important.

Most of the experiments have been carried out at modest temperatures. At higher temperatures the friction and wear may change dramatically as contaminents are desorbed or as surface films form by chemical reaction.

SESSION III

Summary of Main Presentation

SURFACE-LUBRICANT INTERACTIONS AND FRICTION

Dr A.R. Lansdown

Surface/Lubricant Interactions and Friction at High Temperatures

In any consideration of low heat rejection engines it is recognised that major limitations exist on the thermal and oxidative stability of conventional liquid lubricants.

It is also difficult to obtain any substance which is liquid at normal temperatures but retains adequate viscosity for full fluid film lubrication at higher temperatures above 250 -300 C. As a result there will be a greater tendency for systems to operate in the mixed or boundary lubrication regimes.

All of the types of surface/lubricant interaction which influence boundary lubrication are affected by high temperatures, most of them adversely.

Flash temperatures in sliding contacts cause transient temperatures at asperity contacts which are generally assumed to be of the order of 200 to 300 C higher than the ambient temperature. Recent evidence has suggested that because of the higher modulus and yield stress and the lower thermal conductivity of ceramics, flash temperatures with ceramics may be as high as 1000 C.

Whichever figures are correct, it is certain that the local surface temperatures at sliding contacts in low heat rejection engines will be significantly higher than the already high bulk temperatures, and it is these high local surface temperatures which will control many of the surface/lubricant interactions.

Adsorption is the basic mechanism by which many present boundary additives operate but adsorption becomes considerably less effective at higher temperatures.

Chemisorbed films are much more effective at higher temperatures than adsorbed films, but the present technology of chemisorption is related almost entirely to organic compounds whose stability at high temperatures is likely to be inadequate.

The third important mechanism of present boundary additives is chemical reaction. If chemical reaction is allowed to proceed continuously, then it leads to unacceptable deterioration of bearing surfaces. There is in fact a balance required between lack of reaction in the steady-state situation and adequate reaction at loaded sliding contacts. This is conventionally achieved by the use of additives which are relatively inactive at lubricant bulk temperatures but become sufficiently reactive at flash temperatures.

These conventional EP additives will be unusable if bulk temperatures in LHR engines reach the same levels as current flash temperatures, because the additives will then react continuously, giving corrosive attack on the bearing surfaces.

There is no apparent fundamental reason why new technologies of adsorption, chemisorption or reaction based on inorganic structures should not be developed, but very little basis for such technologies exists at present, and previous work on inorganic additives for high temperatures was disappointing.

It is therefore difficult at present to conceive of a solution to the problem of high-temperature lubrication which does not involve the use of solid lubricants.

If a base oil can be found which has adequate life for use in a recirculating system, then the only well-established boundary additives which can be used above 250 C are solid lubricants such as molybdenum disulphide, graphite, graphite fluoride and possibly PTFE.

For a single-pass system the only one of these which is likely to be environmentally acceptable is graphite.

The alternative is to develop self-lubricating construction materials which will make the use of boundary additives unnecessary. Such self-lubricating materials will almost certainly be composites of solid lubricants in high-temperature alloys or ceramics.

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